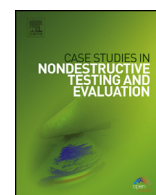


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Eddy current analysis of shipped stainless steel heat exchanger bundle

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ABSTRACT

In this paper, we present the results of a failure analysis done on new heat exchanger tubes, which shows loss of thickness during a EC inspection to establish a prior loss of thickness base line aiming guarantee fitness for service during its working life. The root cause analysis indicates that there is intergranular corrosion due a differential concentration caused by seawater evaporation inside the tubes during the ship transit from the port of origin in China to the destination port in Brazil.

The intergranular corrosion depth showed by root cause failure analysis is smaller than that showed by EC inspection. We attribute the EC inspection results deviation to a tube magnetisation due to mechanical stress and to a secondary phase due to an incomplete solubilisation after tube conforming and welding.

Traditionally, these tubes are visually inspected and deemed acceptable but our conclusions reveal that eddy current testing is capable of detecting some corrosion anomalies which makes the tubes unfit for service.

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Introduction to the case study

Ensuring the integrity of industrial equipment operating under pressure such as heat exchangers is a global concern to the owners of such equipment [1]. Failure in service can cause severe accidents involving loss of life, environmental damage, damage to property and to the reputation of the owner of the equipment, interruption to the production and maintenance costs [2].

It is common practice for all tubes manufactures to protect both tubes end with plastic caps to prevent the ingress of water and other materials, which can cause damage to the internal tube surface [1], as shown in Fig. 1 below.

A heat exchanger manufacturer based in Brazil was expecting a shipment of heat exchanger tubes from China. The heat exchanger owner contracted Technotest to perform an NDT inspection prior to receiving the heat exchanger at their site aiming establish a base line for loss of thickness for subsequently inspection during the equipment working life. It is however common practice before the commissioning to inspect the equipment to ascertain its fitness for service regarding corrosion and other damages to guarantee a secure in-service life according ASME code [3]. The inspection NDT method used for this depends on the construction standards. The most often used NDT method for stainless steel heat exchangers

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Fig. 1. Plastic caps cover at the end of the tube prior to shipment.

Table 1
Differential channels parameters.

Essay parameters	Channel 3	Channel 4	Parameters (Mixer 1)	Mixed channel 1 (Mixer 1)
Frequency	60 kHz	40 kHz	Gain	300
Phase angle	81°	324°	In Phase	00
Gain	95	115	Out Phase	24
Horizontal Sens. – H	1.00	1.00	H Weight	87
Vertical Sens. – V	1.00	1.00	V Weight	51
Filter LP	70	70	H (Sens.)	1.00
			V (Sens.)	1.00

Table 2
Parameters relation between loss of thickness and phase angle.

Percentage loss of thickness	Phase Angle Channel 3	Phase Angle Mixed Chanel 1 Mixer 1
Through hole 100%	35°	35°
External hole 80%	56°	50°
External hole 60%	75°	69°
External hole 40%	106°	93°
External hole 20%	111°	100°

tubes bundles is eddy current testing [3]. This NDT method is sensitive to localised corrosion, general corrosion and cracks on both tube surfaces, internal and external [3].

Method and results

The NDT method used to carry out this first inspection was eddy current. The heat exchanger tube bundle was made from a seamless stainless steel ASME-SA 213 TP 304L, with 25.4 mm internal diameter and 2.77 mm thickness prior to receiving it at the manufacturer's site. The eddy current inspection was performed according ASME code, section V, article 8, and appendix 1 [3], using conventional internal probe with 85% fill factor with the test parameters showed in Table 1 and Table 2.

After completion, the heat exchanger tubes inspection shows a loss of thickness to the internal tube surface as shown in the tube sheet in Fig. 2.

The tube sheet map received from Technotest shows many tubes with general corrosion between 0 and 20%, some tubes with general corrosion between 61 and 80%, 3 tubes obstructed and one tube with general corrosion between 81 and 100%.

These results were not expected for new tubes, specially one tube with general corrosion between 81 and 100%, and it required an in-depth analysis by other methods to determine the root failure cause. Aiming to determine the root cause, two tubes were removed from the tube bundle. One of the tubes has no loss of thickness is identified as sample 2 and the other which shows a loss of thickness between 81 and 100% under eddy current test is identified as sample 1. Both samples were put through a mechanical, chemical and metallurgical analysis. The tubes were cut in the middle and examined for indications of corrosion.

The analysis undertaken were:

- Visual inspection to verify any possible indications of corrosion

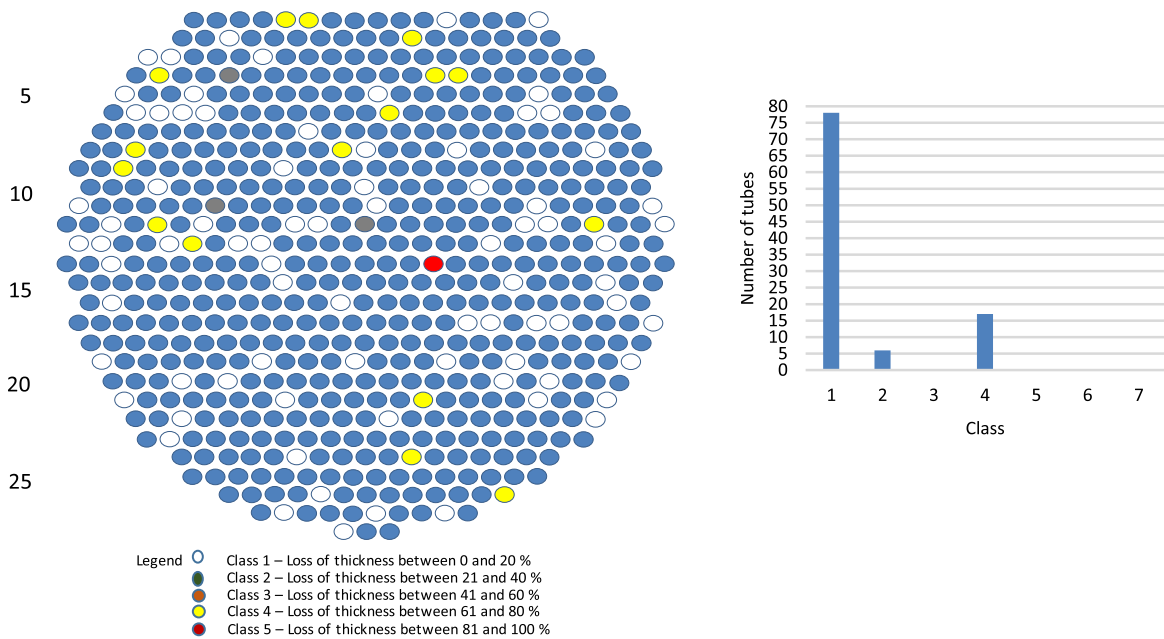


Fig. 2. Tube sheet map after eddy current inspection and number of tubes per class.



Fig. 3. Identification of samples removed from tube bundle, where no corrosive process is observed but some defects from the mechanical process of lamination are present.

- Dimensional measurement of tubes thickness to detect any thickness variations that could explain the eddy currents results
- Profile measurements using a micro hardness Vickers test to verify any possible lack of tube heat treatment during fabrication process
- Chemical analysis to determine any possible changes in the chemical composition incompatible with the material requested on the equipment project
- Micrographic analysis to verify any microstructural change that could explain the results

The visual inspection of the tube shows some defects due to the mechanical formation process but no indication of any corrosive process, as shown in Fig. 3. These lamination defects can indeed be a consequence of a corrosive process due to concentration or differential aeration if any solution contains corrosive salts to stainless steel.

In order to see if there really is no corrosive process under these laminations defects, a macro analysis using a Stereoscopy model SMO-01 was carried out. The macro analysis does not show any corrosive process as shown in Fig. 4.

The dimensional thickness tube analysis does not show any significant variation that could explain the results from the eddy current test. The results from dimensional analysis are shown in Table 3.

The chemical analysis does not show any deviation from a typical chemical composition for a stainless steel ASME-SA 213 TP 304 that could explain any corrosive process. The result of chemical analysis is shown in Table 4.

The microstructural analysis from the transverse tube section shows intergranular corrosion in those tubes that present loss of thickness in an eddy current test. The matrix presents some carbide at grain borderlines and shows some carbide in the matrix. The results from microstructural analysis are shown in Fig. 5.

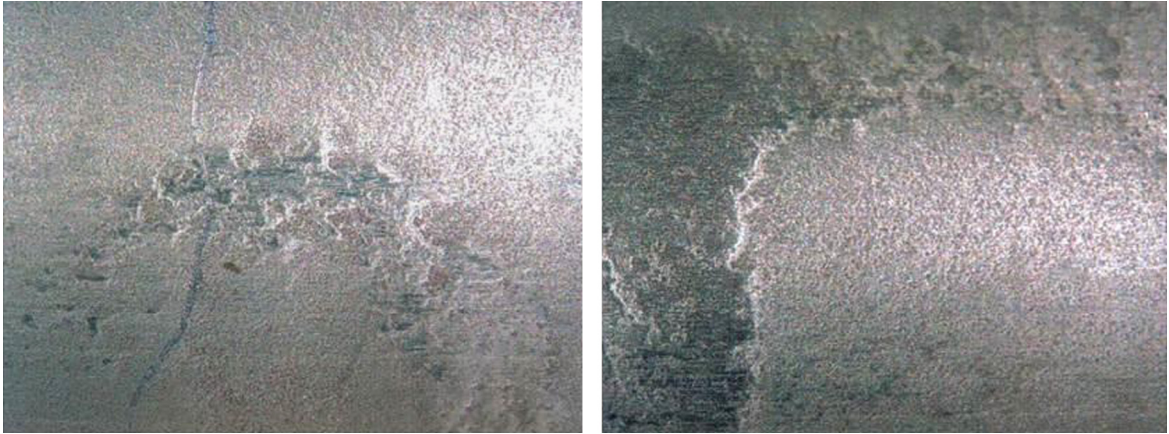


Fig. 4. Regions of lamination defect without any corrosive process on the internal tube surface of Sample 1.

Table 3

Dimensional thickness measurements results.

Point	Sample 1	Sample 2
1	2.70	2.70
2	2.75	2.68
3	2.68	2.70
4	2.70	2.70
5	2.77	2.70

Table 4

Chemical tube analysis.

Element (%)	C (Max)	Mn (Max)	Si (Max)	P (Max)	S (Max)	Cr	Ni
Sample	0.016	0.773	0.409	0.041	0.005	18.375	8.042
Standard	0.080	2.0	1.0	0.045	0.030	18–20	8.0–10.5

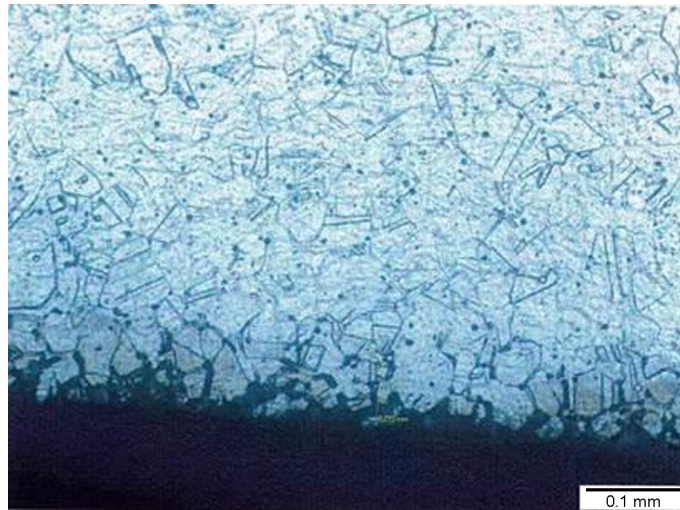


Fig. 5. Micrograph from tube transverse section, 200 X enlarging, acid oxalic etching.

Discussion

It is known that stainless steel shows good resistance to several media especially those containing chlorides [4]. The presence of carbides in grain boundaries and some sigma phase in the matrix comes from improper solubilisation treatment after manufacturing and welding process [5]. The mechanical and welding process can magnetise the stainless steel and these mechanical magnetisations can cause interference in EC inspection. These carbides and sigma phase appear in

the grain boundaries and matrix when the cooling rating is not sufficiently high to prevent the formation of these micro constituents. The carbides and sigma phase make the stainless steel more susceptible to corrosion and hence reduce the service life of heat exchange tubes when in presence of corrosive media like seawater.

The carbides formed around grain boundaries are in the vicinity of the grains that are poor in chromium rather than the centre of grains. Due to this difference in the chemical composition the carbides become, relative to the centre of grain, anodic because of the halides such as chlorine and will cause intergranular corrosion in this area [6,7].

It remains intriguing to explain intergranular corrosion in stainless steel far from the seawater or other environments containing halides in a new tube bundle. The manufacturer who commissioned the inspection explained that those tubes were bought in China due to their low price. It now became evident from where salt water came to cause intergranular corrosion in new tubes. The tubes had been transported by sea from China to Brazil. It is well probable that during the cargo shipment, some of the tubes lost their protective plastic caps which allowed the sea water to get inside the tube. The cargo hold vapour condensed inside the tubes when the hold is closed as the temperature inside the ship's hold rises and the water from seawater evaporate creating micro regions with a high concentration of chlorine. This chlorine breaks the protective layer of chromium over stainless steel. Once this protective layer breaks it never recomposes and the carbides around the grains boundaries are exposed and begin to corrode.

This process will happen every time the ship stops at each port on its way to Brazil. This type of corrosion is impossible to detect using a visual inspection only NDT methods can reveal the presence of intergranular corrosion.

Conclusion

Although it is common that newly manufactured stainless steel tubes are only inspected visually, it is not always possible to establish their fitness for service. The industry standard of heat exchanger puts a stringent test to ascertain the non-existence of flaws which can lead to failure and fatal consequences. The eddy current testing shows inconsistent results for a new tube, especially those with general corrosion between 61 and 80% and the tube with general corrosion between 81 and 100%. These results were influenced by residual magnetisation that come from improper solubilisation heat treatment, tube mechanical conformation and welding process. Despite the general corrosion be less than 10% of nominal tube thickness the tube bundle is improper to service. The intergranular corrosion is associated to differential chlorines concentration pile formed during the ship travel from China to Brazil. These chlorine ions from salt water condensed inside the tubes destroyed the passivated chromium film over the stainless steel causing intergranular corrosion.

Acknowledgement

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References

- [1] TIS – Transport Information Service. Steel Pipes. 2016. Available from http://www.tis-gdv.de/tis_e/ware/stahl/rohre/rohre.htm#informationen. Accessed on August 2016.
- [2] Asset Insights. CoF – Consequence of Failure. 2016. Available from http://www.assetinsights.net/Glossary/G_Consequences_of_Failure.html. Accessed on August 2016.
- [3] BPVC – Boiler and Pressure Vessel Code. Section VIII. Pressure Vessels, Division 1 and Division 2. American Society for Mechanical Engineers. 2010 edition. July 1, 2010. American Society for Mechanical Engineers; 2010.
- [4] Mameng S, Pettersson R. Behaviour of stainless steel in natural seawater. In: Eurocorr 2011. 2011. Available from <http://www.outokumpu.com/SiteCollectionDocuments/Localised-corrosion-of-stainless-steels-depending-on-chlorine-dosage-in-chlorinated-water-Acom.pdf>. Accessed on August 2016.
- [5] Klemetti K, Hänninen H, Kivilathi J. The effect of sigma phase formation on the corrosion and mechanical properties of Nb-stabilized stainless steel cladding. Welding Research Supplement, 17-S-25-S. Available from https://app.aws.org/wj/supplement/WJ_1984_01_s17.pdf, 1984. Accessed on August 2016.
- [6] Silva Andre Luiz Da Costa, Mei PR. Aços e ligas especiais. Edgard Blücher; 2008.
- [7] Roberge PR. Handbook of corrosion engineering. McGraw-Hill; 2000.